Experimental and Theoretical Studies of Ice-Albedo Feedback Processes in the Arctic Basin

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LONG TERM GOALS

Our overall goal is to develop a quantitative understanding of processes that collectively make up the *ice-albedo feedback mechanism*. This mechanism is generally believed to be a key factor in amplifying natural variations within the earth's climate system. Central to achieving this understanding is learning more about how shortwave radiation is absorbed and distributed in the ice pack and upper ocean, and how this distribution affects the regional heat and mass balance of the ice cover. Complicating the problem are a variety of issues related to the extreme sub-grid scale variability of the Arctic ice cover and to how such variability can be accounted for in large-scale models. Our long-term goal is to develop accurate formulations of major ice-albedo feedback processes in a form suitable for inclusion in climate and general circulation models.

OBJECTIVES

We are investigating a variety of specific problems related to the interaction of shortwave radiation with the ice and ocean. Of particular interest are factors that affect the amount of light transmitted to the ocean through the ice cover. Overall, the research addresses the following general questions: (1) How is shortwave radiation that enters the ice-ocean system partitioned between reflection, surface melting, internal heat storage, and transmission to the ocean, and how is this partitioning affected by the physical properties of the ice, snow cover, melt ponds and distribution of contaminants? (2) What is the areal distribution of ice, ponds and leads in perennially ice-covered regions; how does this distribution vary with time; and how does it affect area-averaged heat and mass fluxes? (3) What are the crucial variables needed to characterize ice-albedo feedback processes and their effect on the heat and mass balance of the ice pack, and how accurately can they be treated through simplified models and parameterizations?

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14. ABSTRACT
Our overall goal is to develop a quantitative understanding of processes that collectively make up the ice-albedo feedback mechanism. This mechanism is generally believed to be a key factor in amplifying natural variations within the earth???s climate system. Central to achieving this understanding is learning more about how shortwave radiation is absorbed and distributed in the ice pack and upper ocean, and how this distribution affects the regional heat and mass balance of the ice cover. Complicating the problem are a variety of issues related to the extreme sub-grid scale variability of the Arctic ice cover and to how such variability can be accounted for in large-scale models. Our long-term goal is to develop accurate formulations of major ice-albedo feedback processes in a form suitable for inclusion in climate and general circulation models.

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APPROACH

These issues are being addressed through a combination of field measurements, laboratory observations and theoretical modeling. Field data in support of this work were collected over a complete annual cycle at the SHEBA Drift Station in the Central Beaufort Sea. Measurements were carried out jointly with D.K. Perovich and colleagues from the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) and focused on data needed to estimate the regional input of shortwave energy to the ice and ocean, lateral melting on floe edges, and melt pond evolution, as well as other data needed to improve our understanding of ice-albedo feedback processes in the Central Arctic.

Complementing the field observations were an extensive series of structural and optical measurements carried out in laboratory sea ice samples under a wide range of temperatures (-1 to –34 °C). These data have been used to develop and test a model that relates structural and optical properties in sea ice. Such a model is needed to provide a general description of radiative transfer in sea ice and will form the basis for modeling efforts to predict the optical evolution of the ice cover during the summer melt season. Analysis and interpretation of the experimental data were made possible through development of a two-dimensional Monte Carlo model, which allows us to investigate how horizontal variability affects radiative transfer in sea ice. The model is also being used in the analysis of vertical irradiance profiles collected in bore holes during the SHEBA Project.

WORK COMPLETED

Ongoing analysis of the SHEBA data has shown a surprisingly large amount of heat in the summer mixed layer, leading to total mass losses at the underside of the ice pack that were comparable to those at the upper surface. The origin of this heat appears to have been largely solar radiation transmitted through the ice pack. Since the amount of open water was relatively small, much of this energy must have been transmitted through the ice rather than through leads. Light extinction coefficients for sea ice measured during previous field experiments, however, are too large to explain the amount of heat observed in the water. Because heat transfer from the ocean appears to be a major factor in the SHEBA heat and mass balance, recent efforts have focused on trying to better understand and quantify shortwave transmission by the ice. In particular, we have been: (1) using irradiance profile data to estimate spatial and temporal variations in extinction coefficients, (2) looking at the two-dimensional nature of the radiation field near melt ponds, and (3) continuing to investigate relationships between the optical properties of the ice and its structure. These analyses have required application of both our 2-D Monte Carlo model and our structural-optical model, which, in turn, has led to recent improvements, and refinement of these two models. Summarized below are some results from this work and from the analysis of other basic SHEBA heat and mass balance data, which are contained in five journal papers that were published during the past year. Additional results will be published in several other journal papers, which are either in press, submitted, or in preparation.

RESULTS

<u>Radiative Effects of Soot During the SHEBA Experiment</u>
Previous observations of soot concentration around the periphery of the Arctic Ocean show snow pack concentrations ranging from about 1 to more than 200 nanograms of carbon per gram of snow (ngC/g), with typical values being near 40 to50 ngC/g. Values of this magnitude significantly affect the optical

properties of the ice cover as well surface melt rates and internal heat storage in the ice. During the SHEBA experiment there was concern that soot emitted from the ship could adversely impact the heat and mass balance measurements, producing results that would not be representative of the region. However, soot measurements carried out near the ship in late April and early May 1998 yielded average concentrations of only 4-5 ngC/g over the depth of the snow pack. Measurements made up to 16 km from the ship yielded average background levels of 4.4 ngC/g, similar to values measured in the experimental area on the upwind side of the ship. Results show that soot concentrations in the central Arctic are substantially lower than those found previously in the coastal regions, and that they are insufficient to produce significant decreases in the natural albedos or melt rates.

Seasonal Evolution of Arctic Sea-Ice Albedo

Surface-based spectral and wavelength-integrated albedo values were obtained over multiyear sea ice during SHEBA. Measurements were made every 2.5 m along a 200-m survey line from April through October. Observed changes in albedo were a combination of a gradual evolution due to seasonal transitions and abrupt shifts resulting from synoptic weather events. There were five distinct phases in the evolution of albedo: dry snow, melting snow, pond formation, pond evolution, and fall freeze-up. In April, the surface albedo was high (0.8-0.85) and spatially uniform. By the end of July, the average albedo along the line was 0.4 and there was significant spatial variability, with values ranging from 0.1 for deep, dark ponds to 0.65 for bare, white ice. A comparison between net solar irradiance computed using observed albedos and a simplified model of seasonal evolution shows good agreement, provided that the timing of the transitions is accurately determined.

Ice Mass Balance During SHEBA

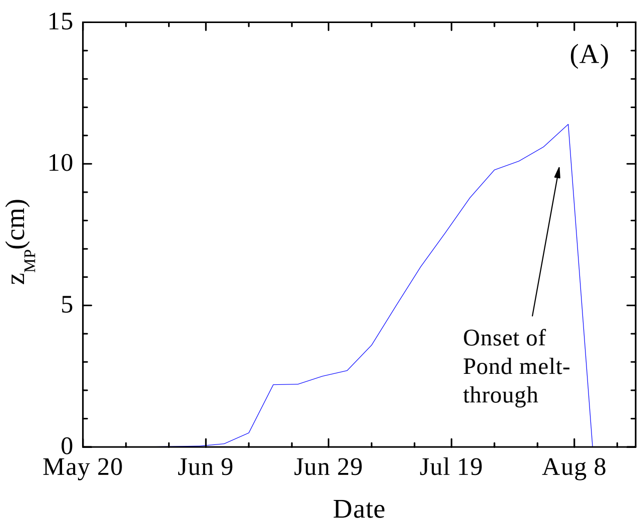
The mass balance of the ice was measured at 135 sites covering a wide variety of ice types, including: first-year ice, ponded ice, unponded ice, multiyear ice, hummocks, new ridges, and old ridges. Initial ice thicknesses for these sites ranged from 0.3 to 8 m, and snow depths varied from a few centimeters to more than a meter. At the end of the experiment year, all of the thickness gauges sites showed a net thinning of the ice and an annual thickness cycle that was qualitatively similar at all sites. Maximum surface melting occurred in July, while bottom ablation peaked in August. Combining results from all sites, we found an average winter ice growth of 0.51 m and a summer melt of 1.26 m, consisting of 0.64 m of surface melt and 0.62 m of bottom melt. Considerable variability was observed between sites in both growth and ablation. The total growth during the 9-month cold season ranged from zero for thick ridged ice to more than a meter for young ice. Ice surface melt tended to be largest in the ponds, while bottom ablation was dominant for ridges.

Hydraulic Controls of Summer Arctic Pack Ice Albedo

The large-scale albedo of sea ice is a key parameter in the energy budget of the polar regions and is central to the Arctic's role in global climate change. We show that Arctic summer sea-ice albedo is critically dependent on the hydrology of surface melt ponds, as controlled by meltwater production rate, ice permeability and topography. Both strong short-term variability as well as the seasonal evolution of the pond fraction (and, hence, the area-averaged albedo) are forced by changes in pond water level on the order of a few centimeters. While some of these forcing functions may be difficult to represent in large-scale models, simulations with a simple hydrological model capture the essential features and variability in pond fractions and depth, identifying a promising alternative path towards predicting rather than prescribing ice albedo in numerical simulations.

Surface Melt Water Storage by Melt Ponds

Substantial amounts of surface melt water are stored, at least temporarily, in melt ponds. Melt water retained by ponds at the end of the summer quickly refreezes, canceling out some of the apparent mass "loss" due to surface ice ablation. To affect the overall mass balance of the ice pack, melt water must run off and enter the ocean. The total amount of surface water is difficult to determine due to constant changes in the area and depth of each individual pond. We overcame this problem using a tide gage and Archimedes principle. By combining measurements of changes in freeboard level with observations of surface ablation, bottom ablation, and melt pond coverage from aircraft surveys, we were able to obtain areally-averaged estimates of the amount of liquid water stored on the surface of a large ice floe at the main SHEBA field site. Figure 1 shows that water storage increased steadily from the onset of melt on 30 May until about 8 August when the amount of water was equivalent to a 12 cm thick layer covering the entire floe. This was roughly 20% of the total summer surface melt. Average pond depths had reached about 48 cm by this time. By 11 August, most ponds melted through the floe, becoming hydraulically connected to the ocean and, in effect, circular leads. In the end, the SHEBA floes were too thin to retain surface melt water throughout the entire summer, but thicker (>1.5 m) floes are likely to have stored upwards of 20% of the summer surface melt by the onset of fall freeze-up.



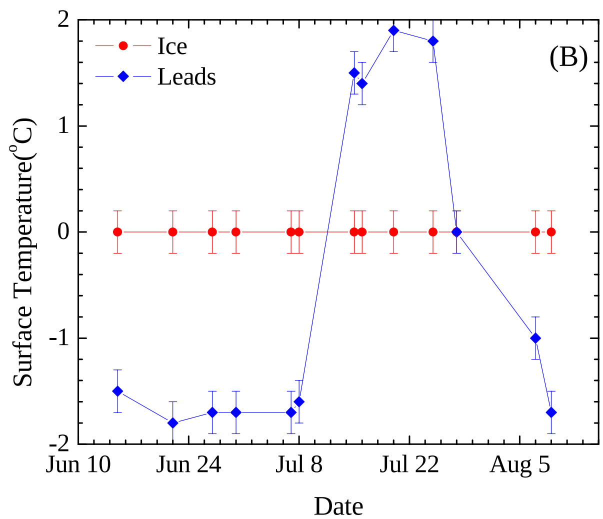


Figure 1. Distributed depth of melt water on the station floe. Depth increased from 0 in early June to a maximum of 12 cm on 8 Aug. Most ponds then melted through and were drained by 11 Aug.

Figure 2. Average summer surface temperatures of leads and bare ice. Lead temperatures increased from –1.8 to +2.0 °C during 8-20 July, dropping back to –1.8 °C during 2 weeks following storm.

Spatial and Temporal Variations in Summer Surface Temperatures

Horizontal surface temperature profiles in the region surrounding the SHEBA station were collected throughout much of the melt season using a helicopter-mounted infrared photometer. Thirteen transects of roughly 200 km each were made during the period. Concurrent aerial photography was used to identify the type of surface being observed. The primary objective was to monitor absorption and buildup of solar heat in the stable water of the leads, a key element in the heat and mass balance. Lead temperatures (Fig. 2) remained near the freezing point until early July when they began to

increase rapidly. The total increase was nearly 4 °C by late July when a storm mixed the heat downward into the mixed layer where it contributed to greatly enhanced bottom melting on the surrounding floes. It is important to note that lead temperatures were generally uniform throughout the region. The analysis also demonstrated the need to take into account the infrared optical depth of the atmosphere in determinations of surface temperatures using aircraft or satellite IR photometry.

Structural-Optical Model

Final development and testing of the structural-optical model has been completed and the results written up for journal publication. The model relates the structural properties of first-year sea ice to its inherent optical properties, quantities needed by advanced radiative transfer models. This model makes it possible to calculate temperature-dependent changes in absorption coefficients, scattering coefficients, and phase functions for the ice from information about its physical properties. The model takes into account scattering by brine inclusions in the ice, gas bubbles in both brine and ice, and precipitated salt crystals. Recent enhancements include improved treatment of hydrohalite precipitation at cold temperatures, as well as inclusion merging and loss of vapor bubbles at warm temperatures. Results show that the structural-optical properties of sea ice can be divided into three distinct thermal regimes: *cold* (T < -23 °C), *moderate* (-23 °C < T < -8 °C), and *warm* (T > -8 °C). Relationships between structural and optical properties in each regime involve different sets of physical processes, of which most are strongly tied to freezing equilibrium. Volume scattering in cold ice is dominated by the size and number distribution of precipitated hydrohalite crystals. Scattering at moderate temperatures is controlled by changes in the distribution of brine inclusions, gas bubbles, and mirabilite crystals. Total volume scattering in this regime is nearly independent of temperature because of a balance between increasing and decreasing scattering related to the thermal evolution of these inclusions. In warm ice, scattering is controlled principally by temperature-dependent changes in the real refractive index of brine (m_{brine}) and by the escape of gas bubbles from the ice. Figure 3A shows model predictions of how scattering by each type of inclusion changes with temperature, while Fig. 3B compares model predictions of the similarity parameter s (a measure of irradiance attenuation caused by scattering) with laboratory observations in natural sea ice. This work was carried out jointly with Dr. B. Light funded under Grant N00014-03-1-0120.

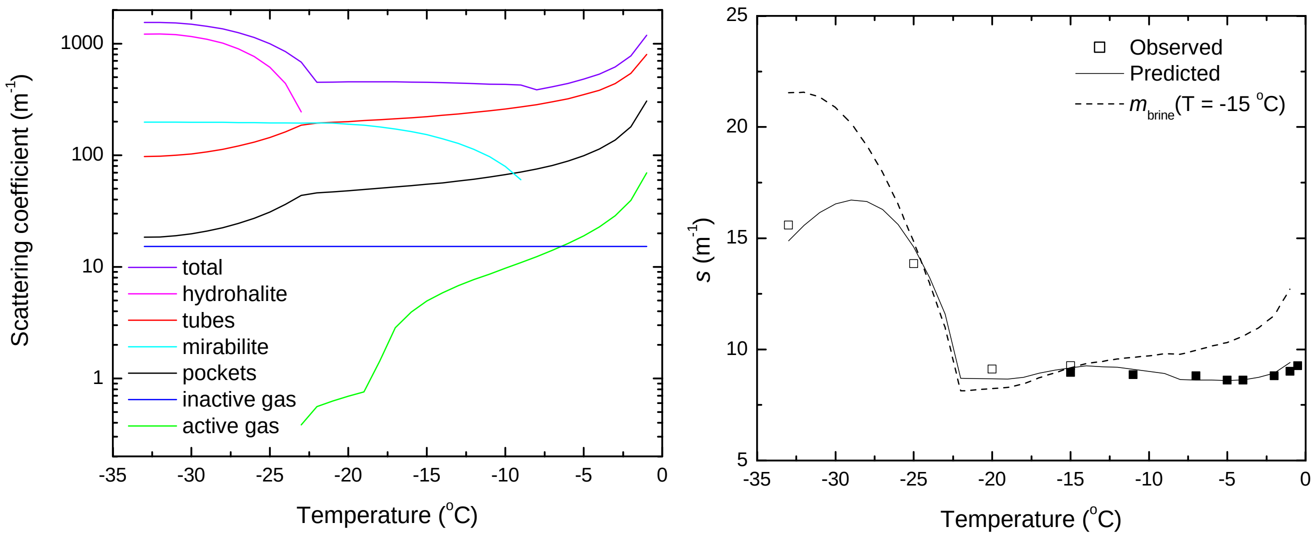


Figure 3 (A) Temperature-dependent scattering coefficients for various types of inclusions present in sea ice as predicted by the structural-optical model. (B) Comparison between observed values of the similarity parameter* s *and predictions by the structural-optical model (solid line) show good agreement at all temperatures. Ignoring the temperature dependence of* m_{brine} *(dashed line) causes* s *to be greatly overestimated at both warm and cold temperatures.

IMPACT/APPLICATIONS

Data obtained during the field effort provide the means to test theoretical models dealing with: (1) the transmission and absorption of light by the ice pack, (2) the role of leads and melt ponds in the regional heat and mass balance, and (3) the storage of solar heat in the water and its interaction with the ice cover. Analysis of irradiance profile data show that previous measurements have significantly overestimated light attenuation by the ice. Recent calculations by D. Hayes have shown that these new, lower values of extinction can explain nearly all the observed heating of the ocean mixed layer during the summer. The laboratory and theoretical studies also suggest that relatively simple parameterizations of radiative transfer in sea ice can be developed for large-scale modeling. We expect that these data and modeling results will lead to an improved understanding of ice-albedo feedback processes that can be used to enhance the accuracy of predictions made by climate models and GCMs.

TRANSITIONS

Our heat and mass balance data collected at SHEBA are archived in the JOSS database and also placed on a CD-ROM which has been widely disseminated to the community. We expect that these data will be used in a variety of process and column modeling studies by ourselves and other groups. Results have been presented at numerous scientific conferences and written up in several journal papers.

RELATED PROJECTS

The work described above is part of a group project being carried out jointly with CRREL investigators funded under Contract N0001497MP30046. Much of the recent work on radiative transfer in sea ice has been carried out in collaboration with Bonnie Light who is currently funded under Grant N00014-03-1-0120. We have also worked closely with other SHEBA Phase 3 investigators studying processes related to: (1) the recycling of solar energy absorbed by the ocean, (2) melt pond and ice cover evolution, and (3) energy exchange with the atmosphere. Data from this project will be used in modeling efforts funded under ONR, SCICEX, NASA-POLES, and NSF to calculate the ice thickness distribution and large-scale heat and mass fluxes.

PUBLICATIONS

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